APPLICATION UNDER UNITED STATES PATENT LAWS

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Invention: METHOD FOR THE CONTROL OF AERO GAS TURBINE ENGINES

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This is a:

☐ Provisional Application

☒ Regular Utility Application

☐ Continuing Application
☐ The contents of the parent are incorporated by reference

☐ PCT National Phase Application

☐ Design Application

☐ Reissue Application

☐ Plant Application

This application claims priority to US Patent Application No. 10/012,376, filed December 12, 2001 and German Patent Application No. DE 100 62 252.6 filed December 14, 2000, both of which are incorporated by reference herein.

SPECIFICATION

METHOD FOR THE CONTROL OF AERO GAS TURBINE ENGINES

This application claims priority to German Patent Application 10062252.6, filed December 14, 2000, which application is incorporated by reference herein.

Background

This invention relates to a method for the control of aero gas turbine engines in aircraft having at least two such engines.

In certain flight phases, some engine frequencies can excite vibrations in the aircraft, these being caused by the rotational speed of the high-pressure shaft (NH) or the low-pressure shaft (NL), respectively. These vibrations are perceived by the passengers as noise or oscillations. Also, since the engines rarely operate at the same rotational speed, interference can occur between the engines. This gives rise to beats or standing waves. Where the rotational speed of the low-pressure shaft is controlled, i.e. only the low pressure compressors are synchronized, the rotational speed of the high-pressure shaft will remain a potential cause of disturbance.

Among others, the causes for different engine behavior are: The disparity of age between engines upon replacement of one of the engines. Inaccuracies in the measured quantities, these resulting in the generation of deviant controlled variables. The unavoidable manufacturing tolerances which entail similar effects.

Normally, aero engines are both considered and controlled individually. Only in specific cases, the interaction of aero engines is taken into consideration, for example in emergency or thrust vectoring situations.

Few cases are known in which both engines are linked together in terms of control during operation. For example, in the case of a failure of the vertical rudder, the two engines can be operated with different thrust, this enabling turns to be flown. Also, thrust vectoring is known in military applications (cf. US-PS 5,769,317 or US-PS 6,105,901, for example).

The state of the art entails many, significant disadvantages. It does not provide for the interaction between two or more engines while making use of the components already available in the engines and in the aircraft. This deficiency leads to a higher noise level in the aircraft cabin. Aircraft manufacturers have to fit more attenuation material, resulting in higher mass and increased costs. Furthermore, higher investments have to be made into vibration reduction during aircraft development.

<p style="text-align:center">Description of the Invention</p>

In a broad aspect, the present invention provides for avoidance of vibrations and the resulting generation of undesired noise during the flight of an aircraft.

It is the principal object of the present invention to remedy said problem by providing a method wherein energy, fluid and/or bleed air is removed from or supplied to at least one engine of an aircraft to control the operation of the at least one engine. Further advantageous aspects of the present invention will be become apparent from the following description.

Therefore, in accordance with the present invention, provision is made for the indirect change of the engine parameters. This can be accomplished by the removal or addition of power, energy, fluids and/or other media. As one of the possibilities, bleed air can be taken off the engine. In accordance with the present invention, said measures will not be applied equally to all engines, but differences between the

individual engines will be permitted and induced deliberately to effect the desired change of the engine parameters.

The present invention, therefore, enables the rotational speeds of the engines (aero gas turbines) to be changed in such a manner that oscillations and vibrations which cause undesired noise are avoided.

As a positive effect, the resultant, additional change in thrust of the individual engines enables vertical rudder trimming to be reduced. Since no aircraft flies absolutely straight, a certain degree of vertical rudder trimming always has to be applied. Of course, this entails a greater aerodynamic resistance and, in consequence, impairs the efficiency of the entire aircraft. As a further positive effect, the measures according to the present invention, by exerting an influence on the engine parameters, provide for compensation of differences in yaw.

Since the negative effects known in the state of the art are mostly limited to a very narrow frequency regime (resonant frequency), a minor shift of the excitation frequency (i.e. the rotational speeds) by the measures according to the present invention can be sufficient to effectively reduce, or completely eliminate, these negative effects.

The method according to the present invention can, for example, be implemented by the following measures:

A hydraulic power transmission (positive/negative) between engines, which comprise hydraulic motors/pumps, can be influenced in dependence of the operating conditions. Taking hydraulic power for aircraft applications from the engines to different

amounts allows the engine parameters to be changed.

A hydraulic coupling of the shafts of an engine enables the rotational speeds to be shifted relative to each other.

The present invention also provides for electric power transmission (positive/negative), which, in particular, can easily be implemented on "fully electric" engines with power exchange between the shafts and the individual engines.

A further, particularly efficient measure is the take-off of bleed air from one of the engines.

Apparently, the present invention provides for a combination of said measures and effects in order to achieve a more effective overall influence on a specific parameter, for example the speed of the low-pressure shaft. Furthermore, such combination can give rise to more degrees of freedom, this enabling secondary parameters, for example the speed of the high-pressure shaft, to be optimized in addition to a primary parameter, for example the speed of the low-pressure shaft. This is particularly advantageous in those cases where the low-pressure shaft is decisive for disturbing vibrations while some disturbing influence is exerted by the high-pressure shaft as well.

In the following, the application of the present invention is specified for two-shaft engines. However, the present invention is also applicable for engines with any number of shafts.

Effect by hydraulic measures

According to the state of the art, individual engines or engine groups are operated in separate control circuits. More specifically, these control circuits are hydraulic

operating circuits (e.g. for actuating the flaps or the undercarriage). In some engine designs, for example, two hydraulic pumps supply one circuit while in others they supply separate circuits. Depending on the arrangement and actuation of valves (addition of valves, if applicable), the engines can be made to contribute a different share to the hydraulic system, i.e. their loading and, in consequence, their parameters will change. Therefore, in the case of two-jet aircraft, these two circuits will mostly have separate tasks. Accordingly, a power exchange between the two engines can be effected by design changes. In the case of three-jet aircraft, the hydraulics of the third engine can be used as redundancy for the two other hydraulic systems. Accordingly, in this case, the power parameters of the engine can also be influenced according to the present invention. On four-jet aircraft, two engines are normally connected to one control circuit, i.e. a power change in terms of hydraulic loading can be used to effect a change of the power parameters of the engine also in the latter case.

A hydraulic coupling of the various shafts of an engine enables both rotational speeds (high-pressure shaft and low-pressure shaft) to be influenced (NL = f(NH)). In the function, NL indicates the rotational speed of the low-pressure shaft and NH indicates the rotational speed of the high-pressure shaft.

Effect by electricity

The statements made in the above for the hydraulics apply almost similarly to electricity. However, in the case of electricity, the take-off of different power from the two engines can be effected much more easily. In the case of "fully electric" engines, power exchange of the individual engines and of shafts between engines can be accomplished very simply.

Effect by customer bleed

Normally, bleed air is tapped during the entire flight, this bleed air being fed by both engines into a common system. If the pressure loss between the point of tapping and mixture is different in the bleed-air systems of either engine, the mass flows will vary accordingly between the two engine systems. This variation will influence either of the two engines in a different manner and will finally result in minor speed changes which are utilizable for the effect according to the present invention.

Therefore, in accordance with the present invention, different conditions are produced in the individual bleed-air systems of the engines. As mentioned above, the rotational speeds of the low-pressure shaft and of the high-pressure shaft (NL or NH, respectively) vary with the differences in air bleed applied to either system. This variation is dependent of the type of control applied (speed of low-pressure shaft, NL or pressure ratio across the engine (thrust parameter, EPR)). Thus, according to the present invention, the regime of resonant vibrations is left.

The difference in the pressure loss by tapping of bleed air which is required can most simply be effected by individually setting the throttle valves available within the system. In extreme cases, one system is closed off completely while the other is left open. To a minor extent, it is also possible to cool the bleed air within the fan air-operated heat exchanger to a different degree. Accordingly, the different tapping of bleed air provides for a degree of freedom in terms of the optimization of the desired parameters (NL, NH, FN (net thrust)).

In the following, the changes proposed in the present invention are explained in light of three, typical flight phases. The tables show extreme cases for bleed air distribution between the two engines, starting with a typical value for the tapping of bleed air. The column headed "normal" shows the values applicable to the tapping of equal quantities of bleed air from both engines. The extreme case - double quantity of bleed air tapped from one engine, no bleed air tapped from the other engine - is shown in the columns headed "abnormal" and "none"

As a result of maximum air bleed, thrust will undergo various changes, these being due to the "EPR bleed air debits" provided in the calculation (EPR = pressure ratio across the engine (thrust parameter)). This uneven thrust distribution creates a yaw moment which is either desired or which must be corrected. In the first case, ΔNH obtained will be larger. In the simplest case, the yaw moment can be avoided by dispensing with the EPR debits. This characteristic, i.e. constant thrust, was approximated in the examples by using a constant NL in the calculation.

The results of the "normal" headed columns are the starting point for the calculations of EPR and NL controls. In the case of EPR controls, thrust, NL, NH etc. will change with air bleed. In the case of NL controls, NL and consequently thrust, by approximation, will remain unchanged, while NH will change.

Take-off

EPR control					
Bleed air	normal	abnormal	none	max. delta	Remarks
LP bleed air [lb/s]	0.5	1.0	0.0	1.0	Typical value
EPR [-]	1.4991	1.4861	1.5144	0.0283	
Net Thrust FN [lbf]	11616.6	11372.1	11902.6	530.5	Average thrust = 11637 lbf, i.e. 20.4 lbf higher
sfc [lb/(lbf *s)]	0.4829	0.4858	0.4801	0.0057	Average sfc un-changed
SOT [K]	1499.2	1495.6	1504.5	8.9	In the worst case, one engine is op-erated 5.3 K hot-ter than normal
NL [rpm]	6644.8	6599.0	6695.6	96.6	
NH [rpm]	14894.5	14866.5	14929.3	62.8	

Table 1: Take-off, EPR control

NL control					
Bleed air	normal	abnormal	none	max. delta	Remarks
LP Bleed air [lb/s]	0.5	1.0	0.0	1.0	Typical value
EPR [-]	1.4991	1.4993	1.4987	0.0006	
Net Thrust FN [lbf]	11616.6	11618.0	11615.3	2.7	Average thrust = 11616.7 lbf, i.e. unchanged
sfc [lb/(lbf*s)]	0.4829	0.4857	0.4801	0.0056	Average sfc = 0.4829 => +0.0%
SOT [K]	1499.2	1505.6	1492.8	12.8	In the worst case, one engine is operated 6.4 K hotter than normal
NL [rpm]	6644.8	6644.8	6644.8	0	Set constant to obtain constant thrust!
NH [rpm]	14894.5	14906.7	14882.3	24.4	

Table 2: Take-off, NL control

If the engine is not "derated", SOT will increase during take-off by 5.3 K (or 6.4 K). A maximum ΔNL of 96.6 rpm and a maximum ΔNH of 62.8 rpm can be achieved.

Cruise

EPR control					
Bleed air	normal	abnormal	none	max. delta	Remarks
LP Bleed air [lb/s]	0.5	1.0	0.0	1.0	Typical value
EPR [-]	1.6786	1.6552	1.6997	0.0445	
Net Thrust FN [lbf]	3682.9	3575.9	3780.6	204.7	Average thrust = 3678.3 lbf
sfc [lb/(lbf *s)]	0.6521	0.6581	0.6470	0.0111	Average sfc = 0.65255 => +0.07%
SOT [K]	1453.9	1451.0	1456.3	5.3	In the worst case, one engine is op- erated 2.4 K hot- ter than normal
NL [rpm]	6793.4	6700.0	6883.3	183.3	
NH [rpm]	14235.7	14202.2	14265.0	62.8	

Table 3: Cruise, EPR control

NL control					
Bleed air	normal	abnormal	none	max. delta	Remarks
LP Bleed air [lb/s]	0.5	1.0	0.0	1.0	Typical value
EPR [-]	1.6786	1.6806	1.6759	0.0047	
Net Thrust FN [lbf]	3682.9	3683.2	3682.0	1.2	Average thrust = 3682.6 lb$_f$
sfc [lb/(lbf *s)]	0.6521	0.6599	0.6442	0.0157	Average sfc = 0.65205 => +0.0%
SOT [K]	1453.9	1465.2	1442.5	22.7	In the worst case, one engine is operated 11.3 K hotter than normal
NL [rpm]	6793.4	6793.4	6793.4	0	Set constant to obtain constant thrust!
NH [rpm]	14235.7	14253.9	14216.5	37.4	

Table 4: Cruise, NL control

If the engine is not "derated", the SOT of one engine during cruise will increase by 2.4 K (or 11.3 K). A maximum ΔNL of 183.3 rpm and a maximum ΔNH of 62.8 rpm can be achieved.

Approach

EPR control					
Bleed air	normal	abnormal	none	max. delta	Remarks
HP Bleed air [lb/s]	0.5	1.0	0.0	1.0	Typical value
EPR [-]	1.0132	1.0128	1.0136	0.0008	
Net Thrust FN [lbf]	732.9	712.4	752.0	39.6	Average thrust = 732.2 lbf
Sfc [lb/(lbf *s)]	1.1785	1.2360	1.1275	0.1085	Average sfc = 1.1818 => +0.27%
SOT [K]	972.1	988.0	957.8	30.2	In the worst case, one engine is op-erated 15.9 K hot-ter than normal
NL [rpm]	2898.8	2876.9	2918.4	41.5	
NH [rpm]	11598.0	11598.0	11598.0	0	Since controlled to HI, NHRT26 = const

Table 5: Approach, EPR control

During approach, HI is automatically selected, which means that control is performed to NHRT26; consequently, the calculation here does not indicate a change in speed. Although HI is selected, control is frequently assumed by another control law (e.g. min P30) and can, therefore, be overridden by another parameter just as well, i.e. selection of bleed air, cf. table 6.

NL control					
Bleed air	normal	abnormal	none	max. delta	Remarks
HP Bleed air [lb/s]	0.5	1.0	0.0	1.0	Typical value
EPR [-]	1.0132	1.0138	1.0133	0.0006	
Net Thrust FN [lbf]	732.9	733.1	734.2	1.3	733.7 lbf
sfc [lb/(lbf*s)]	1.1785	1.2138	1.1429	0.0709	Average sfc = 1.17835 => - 0.013%
SOT [K]	972.1	989.7	956.0	33.7	In the worst case, one engine is operated 27.6 K hotter than normal.
NL [rpm]	2898.8	2898.8	2898.8	0	Set constant to obtain constant thrust!
NH [rpm]	11598.0	11634.3	11560.7	73.6	Only possible, if not controlled to HI.

Table 6: Approach, NL control

The increase of sfc with EPR control (more precisely HI control in this case) is quite irrelevant since this flight phase is relatively short. Also, the severe increase of SOT is not dramatic since it takes place from a low starting basis. The small changes in thrust, while probably not being verifiable physically, are assumed to arise from inaccuracies in the calculation program (iterative process).

As becomes apparent from the above, the present invention provides for measures which enable the development of noise and vibrations to be positively influenced by

changing the critical excitation frequencies directly at the source, i.e. the engine, and by shifting them towards an uncritical frequency.

Accordingly, the noise level in the entire area of the cabin will be significantly reduced, in particular near the location of the engines. Furthermore, less attenuation material will be required, which allows the mass of the aircraft to be reduced. The present invention can be implemented by minor changes to the fuselage of the aircraft, this resulting in a very low overall investment. Additionally, the possibility to dispense with, or minimize, rudder trimming will result in reduced fuel consumption and, accordingly, in a larger range.

Summarizing, then, the present invention relates to the exchange, the take-off or addition of media and/or power between the individual shafts of an engine, between individual engines and between the engines and the aircraft. Thus, the present invention provides for additional degrees of freedom enabling engine parameters to be addressed in terms of a reduction or avoidance of negative resonances or beats.

The present invention relates to any number of engines on an aircraft and to any number of engine shafts. In accordance with the present invention, hydraulic power, electric power or air bleed can be influenced, for example.

List of abbreviations

EPR	Pressure ratio across the engine (thrust parameter)
FN	Net thrust
ISA	International standard atmosphere
NH	High-pressure shaft speed
NHRT26	Aerodynamically corrected high-pressure shaft speed
NL	Low-pressure shaft speed
sfc	Specific fuel consumption
SOT	Total entry temperature at the high-pressure turbine
HI	High Idle
HP	High Pressure